U. S. NAVAL AIR DEVELOPMENT CENTER

JOHNSVILLE, PENNSYLVANIA

Aeronautical Electronic and Electrical Laboratory

REPORT NO. NADC-EL-61122 13 MAR 1962

FEASIBILITY OF APPLYING THE LINEAR CLASS C POWER AMPLIFIER TO SINGLE SIDEBAND RADIO

FOUNDATIONAL RESEARCH TASK NO. 6105A OF
WEPTASK No. R360FR102/2021/R011-01-001

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I N T R O D U C T I O N

Task No. 6105A was established as a project of the NAVAIRDEVCEN Foundational Research Program for the investigation and development of ways to reduce the effects of interference in airborne communication systems. As a phase of this Task, a study was initiated to determine the feasibility of applying the high-level, linear, Class C power amplifier to Navy single-sideband (SSB) communication systems. The high-efficiency, Class C final power amplifiers are now used in amplitude-modulated (AM) transmitters, and amateurs have modified these amplifiers for use in their linear SSB systems.

C I R C U I T   A R R A N G E M E N T

The schematic diagram of the Class C linear power amplifier, tuned to 7.2 mc and used for the investigation, is shown in figure 1. A breadboard model of the amplifier was constructed for test purposes.

The amplifier operates as follows: When no r-f signal drive is applied to the 813 tube, no current flows in the grid circuit, and there is no bias on the grid of the clamp tube 6L6. Under this condition, the 6L6 draws heavy plate current that produces a large voltage drop across the screen resistor (40 k), thereby decreasing the voltage on the screen of the 813 and decreasing the plate current. When an r-f signal drive is applied to the grid of the 813, grid current flows and develops a negative bias on the grid of the 6L6. This negative bias decreases the plate current flow of the 6L6, and in turn, decreases the potential drop across the screen resistor of the 813, thus increasing the screen grid voltage and plate current to an optimum value. The amplifier now approaches its intended mode (Class C) of operation.

C I R C U I T   C H A R A C T E R I S T I C S

STATIC CHARACTERISTICS

To determine the power output, linearity, and efficiency of the amplifier, it was necessary to first determine the static characteristics

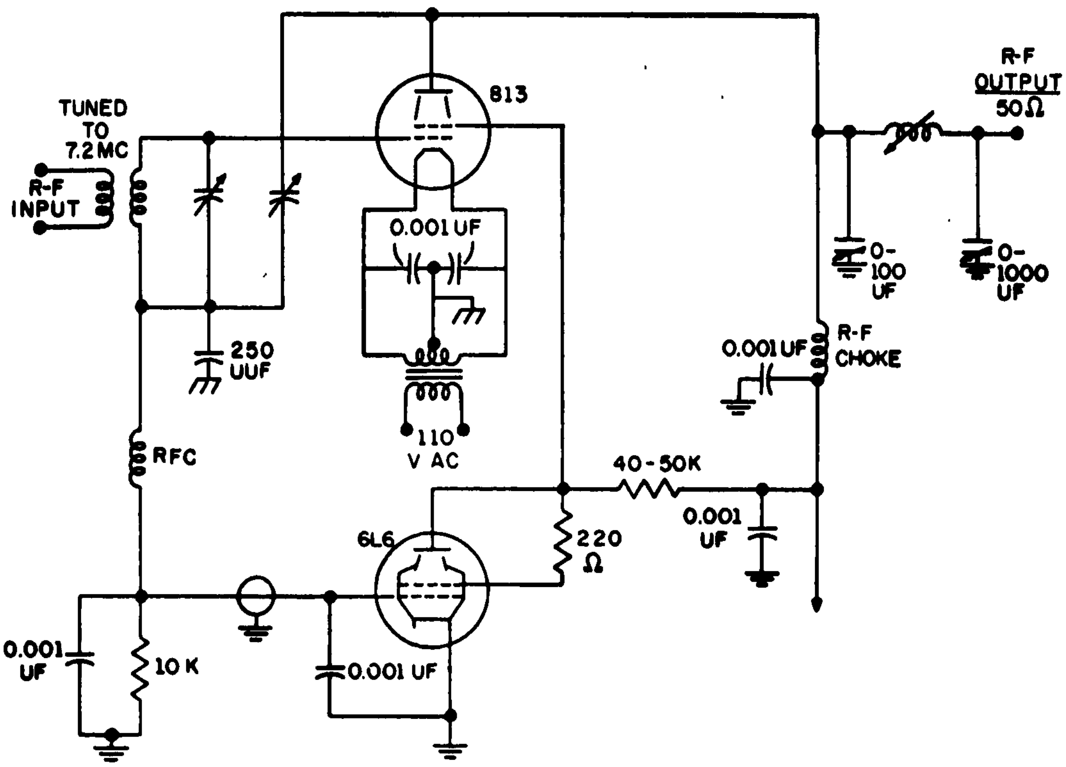

FIGURE 1 - Schematic Diagram of Linear Power Amplifier Used for Analysis

of the amplifier. Normally this can be done for a tetrode tube (813) by obtaining the characteristics curves from the relationship:

$$I_p = f\,(E_g, E_p, E_{sg}), \tag{1}$$

where: I_p = instantaneous plate current, and

E_g, E_p, E_{sg} = instantaneous grid, plate, and screen grid voltages. Under this arrangement, the screen grid voltage E_{sg} is held constant and the constant current contour curves for I_p are plotted with E_p and E_g as the only variables (figure 2).

However, these curves cannot be applied to the linear amplifier because the 6L6 tube controls the screen grid voltage of the 813 tube. But, since the bias on the 6L6 controlling the 813 screen grid voltage is a function of the r-f grid drive, it is possible to eliminate the screen voltage E_{sg} as a variable and plot a static characteristic curve for the amplifier as shown in figure 3. Justification for this action is as follows:

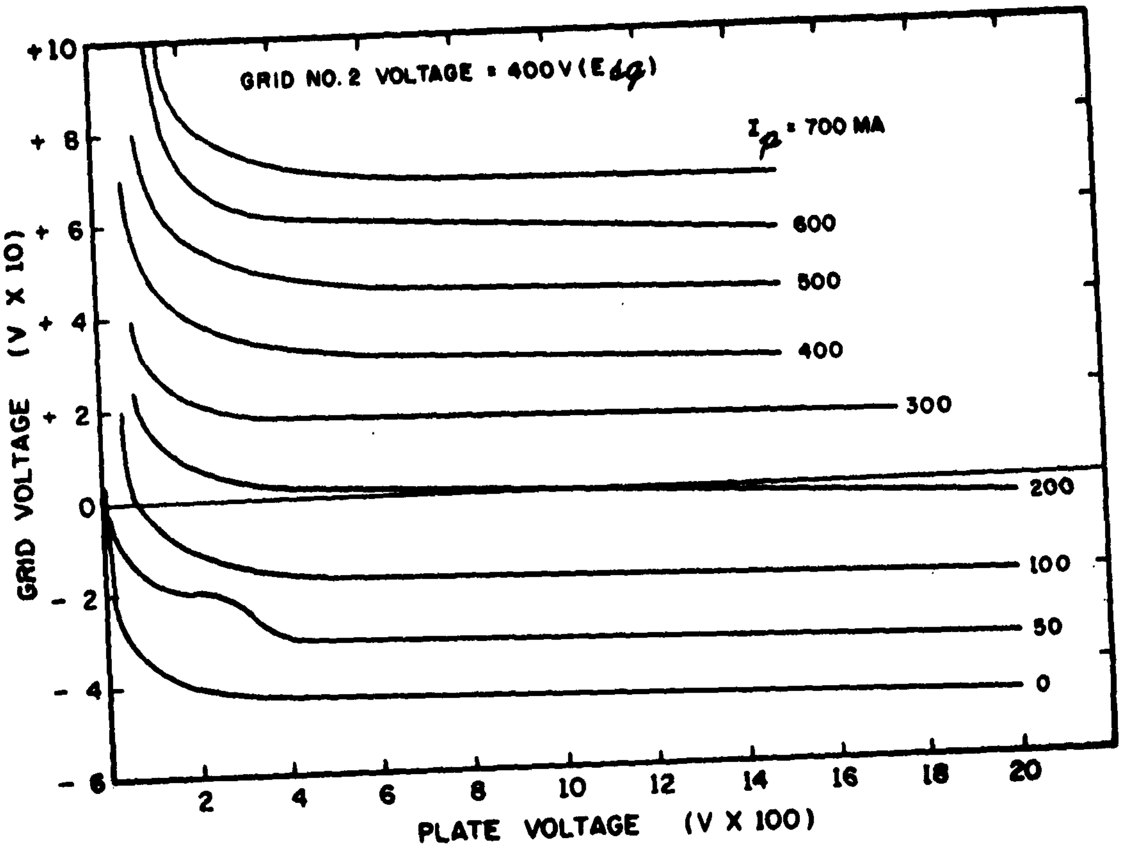

FIGURE 2 - Constant Current Characteristics of 813 Tube

For the 813:

$$I_{p813} = f\ (E_g,\ E_p,\ E_{sg})$$

$$\Delta I_{p813} = (\partial I_p/\partial E_g)\Delta E_g + (\partial I_p/\partial E_p)\Delta E_p + (\partial I_p/\partial E_{sg})\Delta E_{sg} \tag{2}$$

$$\Delta I_{p813} = g_m \Delta E_g + (1/r_p)\Delta E_p + g_{m'}\Delta E_{sg} \tag{3}$$

For the 6L6:

$$\Delta I_{p6L6} = f\ (E_g,\ E_p) \tag{4}$$

$$\Delta I_{p6L6} = g_{m''}\Delta E_g + (1/r_p)\Delta E_p \tag{5}$$

where:

$g_{m'}$ = screen transconductance $(\partial I_p/\partial E_{sg})$ for the 813

g_m and $g_{m''}$ = transconductance $(\partial I_p/\partial E_g)$ for the 813 and 6L6 respectively

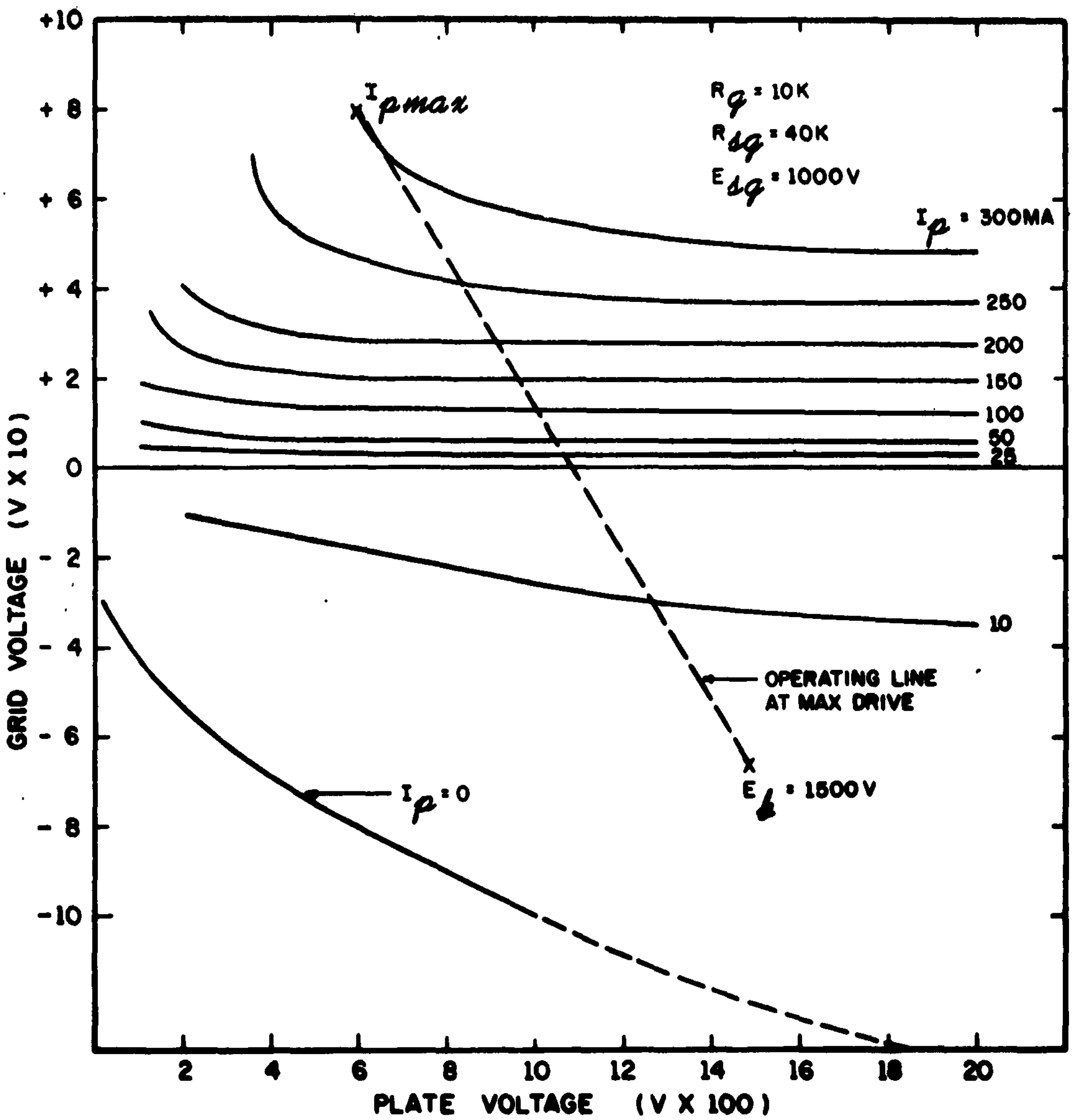

FIGURE 3 - Constant Current Characteristics of Composite Amplifier

r_p = plate resistance $(\partial E_p/\partial I_p)$.

But, $\Delta E_p = -\Delta I_p R_L$, where the load resistance for the 6L6 (R_{L6L6}) equals the screen grid resistance for the 813 (R_{sg813}).
Then, equation (5) reduces to:

$$\Delta I_{p6L6} = \left[g_{m''} r_p/(r_p + R_{sg})\right]\Delta E_g. \quad (6)$$

By substituting $\Delta E_{sg813} = \Delta E_{p6L6} = \Delta I_{p6L6} R_{sg}$, the equation for the composite amplifier becomes:

$$\Delta I_p = g_m \Delta E_{g813} + (1/r_p)\Delta E_{p813} + g_{m'}\left(\frac{g_{m''} r_p}{r_p + R_{sg}}\right)_{6L6} R_{sg}\Delta E_g. \quad (7)$$

However,

$$E_{g6L6} = f\ (E_{g813}), \text{ and} \quad (8)$$

$$\Delta E_{g6L6} = \alpha\Delta E_{g813}. \quad (9)$$

Therefore:

$$\Delta I_p = g_m + g_{m'}\left(\frac{g_{m''} r_p \alpha}{r_p + R_{sg}}\right)\Delta E_g + (1/r_p)\Delta E_p. \quad (10)$$

The equation thus reduces to the desired from, permitting the plot of the composite static characteristic curves without having to solve for the various tube parameters.

The relationship (α) was determined by opening the 10-k grid resistor to the input of the 6L6 and measuring the grid current (I_c) developed in the grid circuit of the 813 as a function of the r-f grid drive voltage (E_g) and plate voltage (E_p), as shown in figure 4. As this curve indicates, the grid current (I_c) is independent of the plate voltage, and a constant ratio of $I_c/E_g = (4/50) \times 10^{-3}$ is obtained over the linear range as shown in figure 5. Since the grid bias (E_c) of the 6L6 is equal to the grid current (I_c) times the grid leak resistance (R_g = 10 k), the ratio of the peak grid drive (E_g) to the grid bias on the 6L6 is

$$E_g/I_c R_g = E_g/E_c = 50/(4 \times 10^{-3} \times 10^4) = 1.25/1.$$

To check the accuracy of the above measurements, made at 7.2 mc, the following analysis was made:

$$\text{Letting } |E_g| = |E_{gm}| - |E_c|, \quad (11)$$

$$\text{and} \quad |E_c| = |E_{gm}| \sin(\pi - \theta)/2, \quad (12)$$

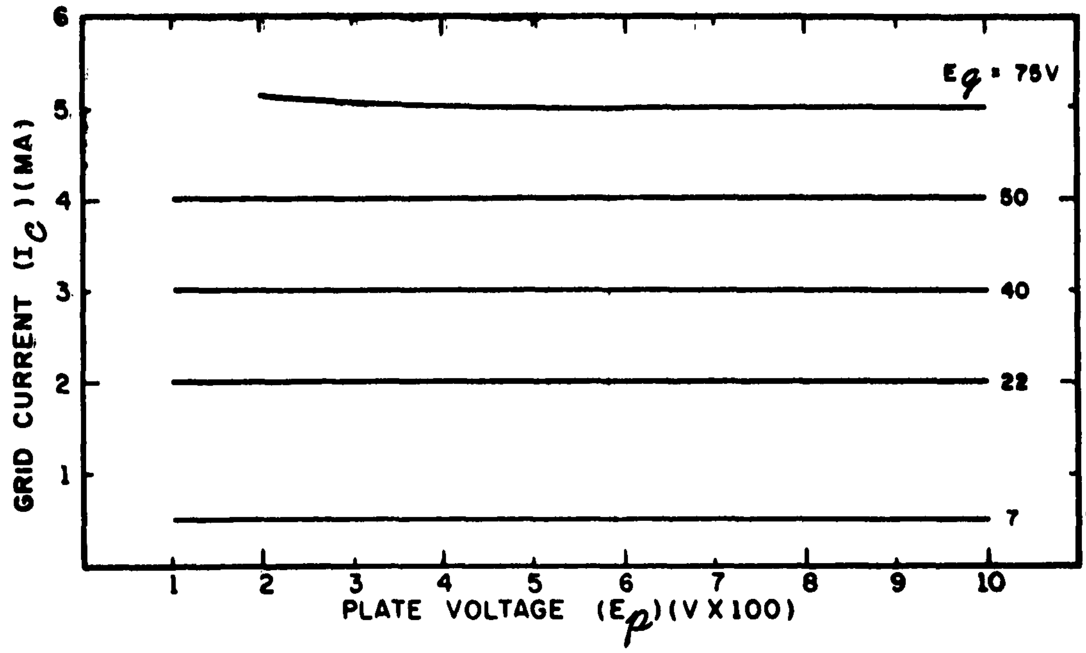

FIGURE 4 - Constant Grid Voltage Contours for 813 Tube

where E_{gm} = peak driving voltage; and assuming conductivity for 130 degrees (θ = 130) of the cycle, then:

$$|E_c| = |E_{gm}| \sin 25^\circ, \text{ and} \tag{13}$$

$$|E_g| = (|E_c|)/\sin 25^\circ - |E_c| = |E_c|[(1 - \sin 25^\circ)/\sin 25^\circ]. \tag{14}$$

Therefore:

$$|E_g|/|E_c| = 1.36. \tag{15}$$

Thus, the relation of E_g to E_c determined by test was approximately equal to that of an ideal case.

The static constant current contours of the amplifier were determined as shown in figures 3 and 6 by using the above relationship. It should be noted that equal negative bias was applied to the 6L6 to obtain negative values for the grid voltage (E_g), and negative bias equal to four-fifths of E_g was applied to the 6L6 for a positive value of grid drive (E_g). (The plate voltage supply varied from 0 to 1500 v dc, and the screen voltage supply was held constant at 1000 v dc.)

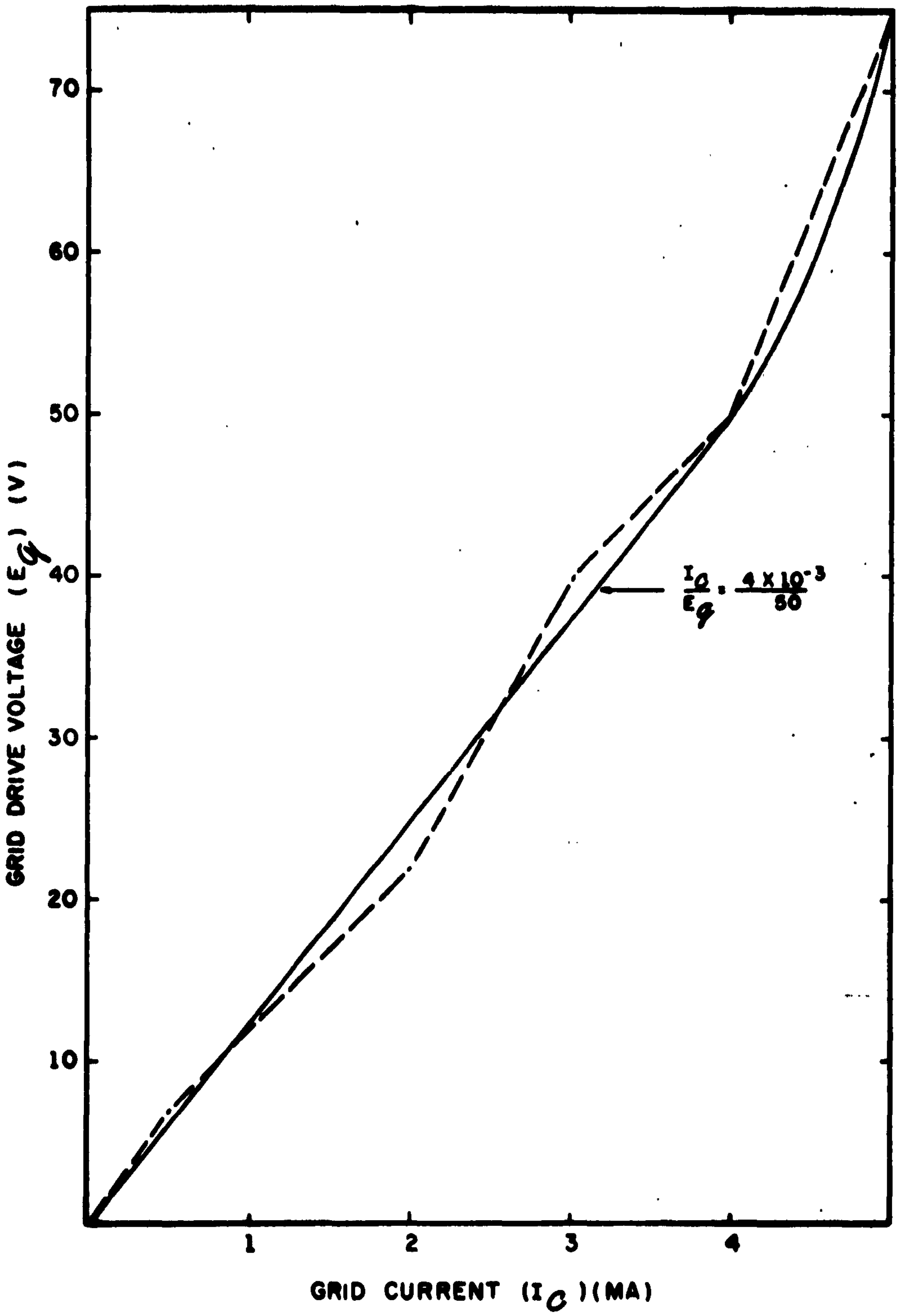

FIGURE 5 - Ratio of Grid Drive to Grid Current for 813 Tube

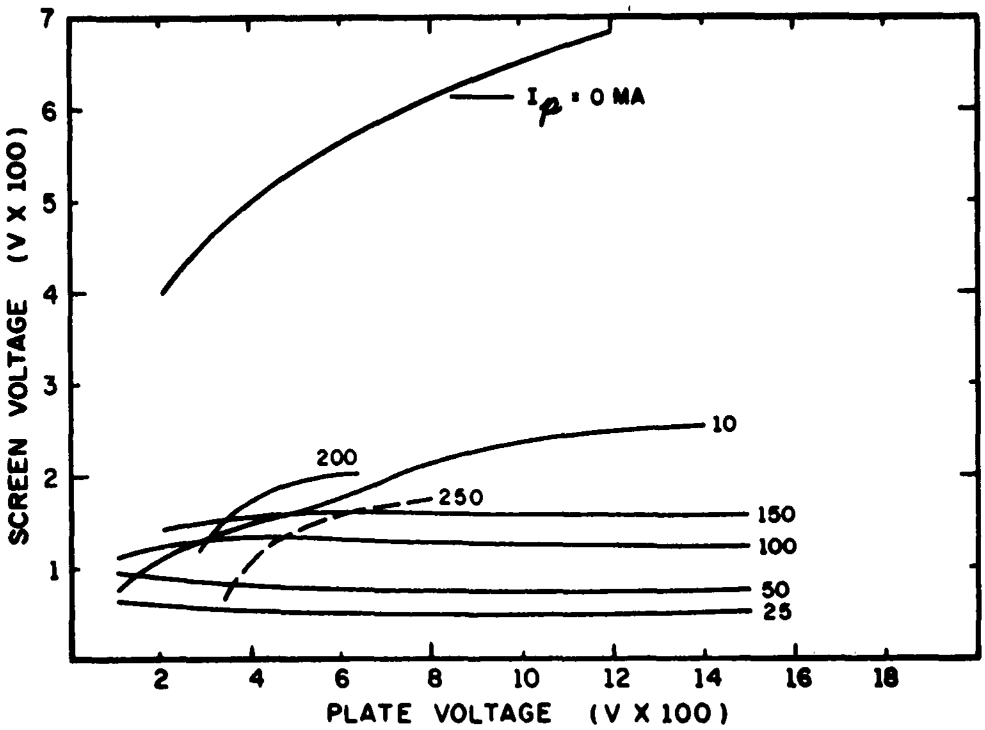

FIGURE 6 - Constant Current Contours for Composite Amplifier as a Function of Screen and Plate Voltages

POWER OUTPUT AND EFFICIENCY

By utilizing the constant current contours given in figure 3, the operating parameters of the amplifier in the Class B mode were calculated as follows:

Single Tone Input

1. Plate supply E_b = 1500 v dc; screen supply E_{sg} = 1000 v dc.

   I_{pmax} = 300 ma

   $I_b = I_{pmax}/\pi$ = 96 ma

   $P_{in} = I_bE_b = 96 \times 10^{-3} \times 1500$ = 144 w

   E_{pmax} = 1500 v; E_{pmin} = 600 v

$P_{out} = I_{pmax}(E_b - E_{pmin})/4E_b$

$= 300 \times 10^{-3} \times (1500 - 600)/(4 \times 1500) = 68.5$ w.

$Eff = \pi(E_b - E_{pmin})/4E_b = \pi(1500 - 600)/(4 \times 1500) = 47\%$.

For the grid circuit, when I_p is maximum:

$E_g = 80$ v

$E_c = -4E_g/5 = -64$ v

$I_c = E_c/R_g = 6.4$ ma ($R_g = 10$ k)

$E_{gmax} = E_g + E_c = 80 + 64 = 144$ v (peak)

$P_d = 0.9E_{gmax}I_c = 0.9 \times 144 \times 6.4 \times 10^{-3} = 0.83$ w

$P_g = P_d + E_cI_c = 0.83 + 64 \times 6.4 \times 10^{-3} = 1.24$ w.

The test results, using a Collins Radio Company 32S-1 as an exciter at 7.2 mc, were:

$E_{gmax} = 180$ v, $I_c = 5.5$ ma at saturation.

$P_{out} = 65$ w

$P_{in} = 135$ w

Plate Eff = 48%

2. Single Tone Input, with $E_b = 2000$ v dc, and $E_{sg} = 1000$ v dc.

$E_b - E_{pmin} = 2000 - 600 = 1400$ v

$P_{out} = 300 \times 1400 \times 10^{-3}/4 = 105$ w

$P_{in} = 300 \times 10^{-3} \times 2000/\pi = 192$ w

$Eff = \pi \times 1400/(4 \times 2000) = 54\%$

The test results were:

$P_{out} = 110$ w

$P_{in} = 200$ w

Plate Eff = 55%

Two Tone Input

E_b = 2000 v dc, E_{sg} = 1000 v dc (supply)

I_{pmax} = 300 ma, E_{pmin} = 600 v

$I_b = 2I_{pmax}/\pi^2 = 2 \times 300 \times 10^{-3}/\pi^2 = 61$ ma

$P_{in} = I_b E_b = 61 \times 10^{-3} \times 2000 = 131$ v

$P_{out} = I_{pmax}(E_b - E_{pmin})/8 = 300 \times 10^{-3} \times (2000 - 600)/8 = 53$ w

Eff = P_{out}/P_{in} = (53/131) x 100 = 41%

Plate dissipation = $P_p = P_{in} - P_{out}$ = 78 w

The test results, with the Collins Radio Company 32S-1 exciters, were:

I_{cmax} = 4 ma at flat top of two-tone signal

P_{out} = 60 w

P_{in} = 156 w

Plate Eff = 39%

DISTORTION

Operational tests and analysis were made on the breadboard model to determine what distortion products were caused by the nonlinear characteristics of the amplifier. The test arrangement is shown in figure 7. The input signal was tapped from the 50-ohm attenuator. The output power was terminated in the 50-ohm wattmeter, and from this load, a sample was fed into the analyzer. The distortion products of the Collins 32S-1 exciter output were determined, and the results are plotted in figure 8 as solid lines. The distortion products of the amplifier with the exciter are plotted as dashed lines in figure 8. The various spurious output that could be measured are listed below:

MIXER PRODUCTS (f_1 = 1000 cps, f_2 = 1700 cps)

Second Order	Third Order	Fourth Order	Fifth Order
*$2f_1$	$3f_1$	$4f_1$	$5f_1$
*$f_1 \pm f_2$	$2f_1 + f_2$	$3f_1 + f_2$	$4f_1 \pm f_2$
	*$2f_1 - f_2$	*$3f_1 - f_2$	$3f_1 + 2f_2$
*$f_2 - f_1$	$2f_2 + f_1$	$2f_1 + 2f_2$	*$3f_1 - 2f_2$
*$2f_2$	*$2f_2 - f_1$	*$2f_2 - 2f_2$	$3f_2 + 2f_1$
	$3f_2$	$f_1 \pm 3f_2$	*$3f_2 - 2f_1$
		$3f_2 \pm f_1$	$4f_2 \pm f_1$
		$4f_2$	$5f_2$

*** Frequencies present within passband plus 600 and 2100 cps AIM products.**

F I N A L   D I S C U S S I O N

The linear amplifier analyzed under this task does not operate in the Class C mode. The correlation of the mathematical analyses and experimental test results for power, efficiency, and linearity indicates that the amplifier operates in the Class B mode. Figures 3 and 6, for I_p = 0, show that a means must provided for clamping the screen voltage to an optimum value (+400 v) to obtain Class C operation. The present amplifier allows the maximum 813 screen voltage to approach the screen supply voltage with increased grid drive and plate voltages.

A comparison of the constant current contours for the 813 tube alone (figure 2) with the curves for the composite amplifier (figure 3) indicates that, with equal grid drive, the maximum power output of the composite amplifier could not equal the power capabilities of the 813 tube alone. The presence of the clamp tube causes the "knee" of the current curves to be displaced to the right, decreasing the maximum allowable plate voltage swing. It also causes the current contours to be displaced upward, requiring higher grid drive to obtain the same peak currents. Thus, the "Class C linear amplifier" analyzed herein is not suitable in its present form for Navy applications.

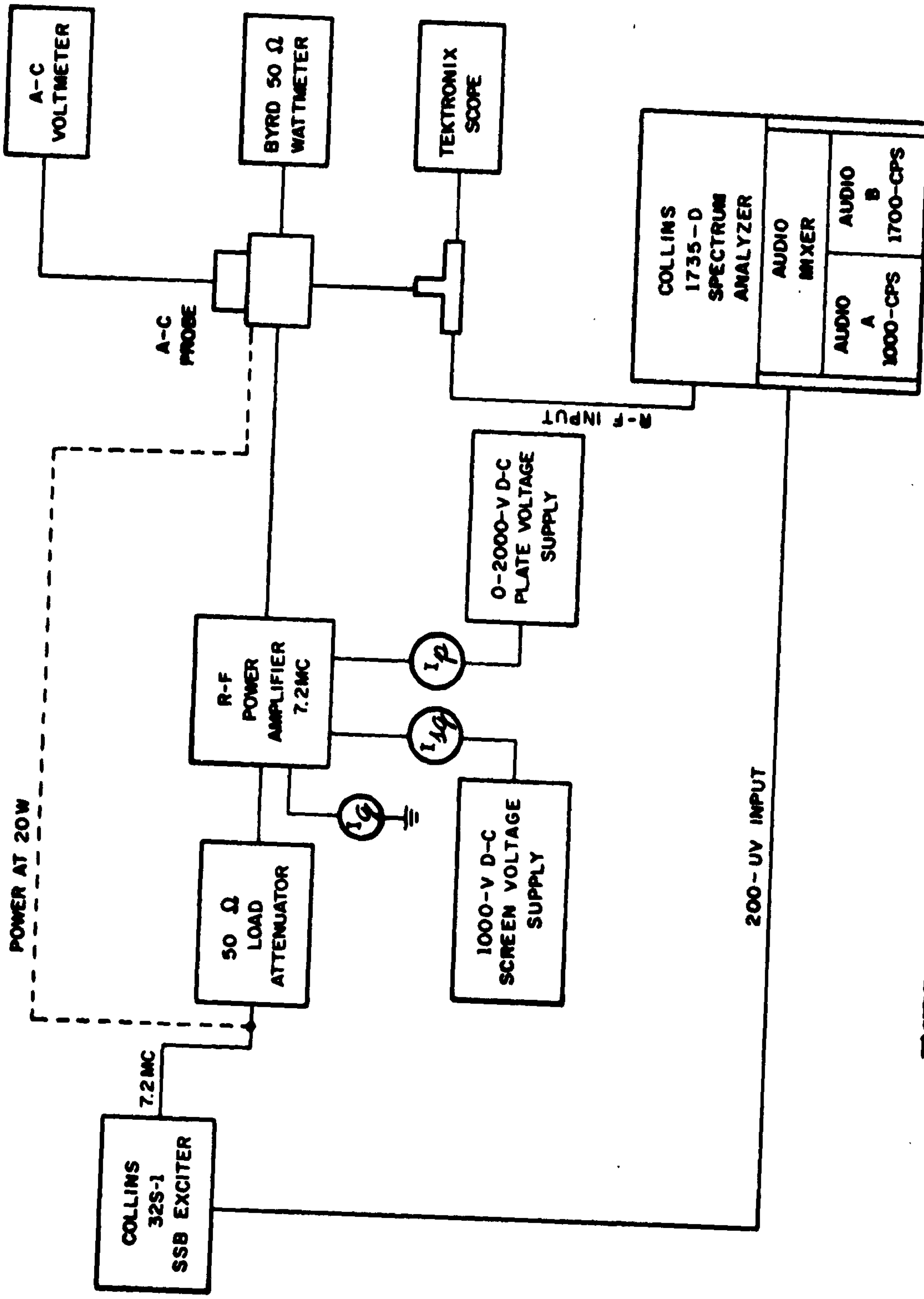

FIGURE 7 - Block Diagram of Two-Tone Test for Spurious Output

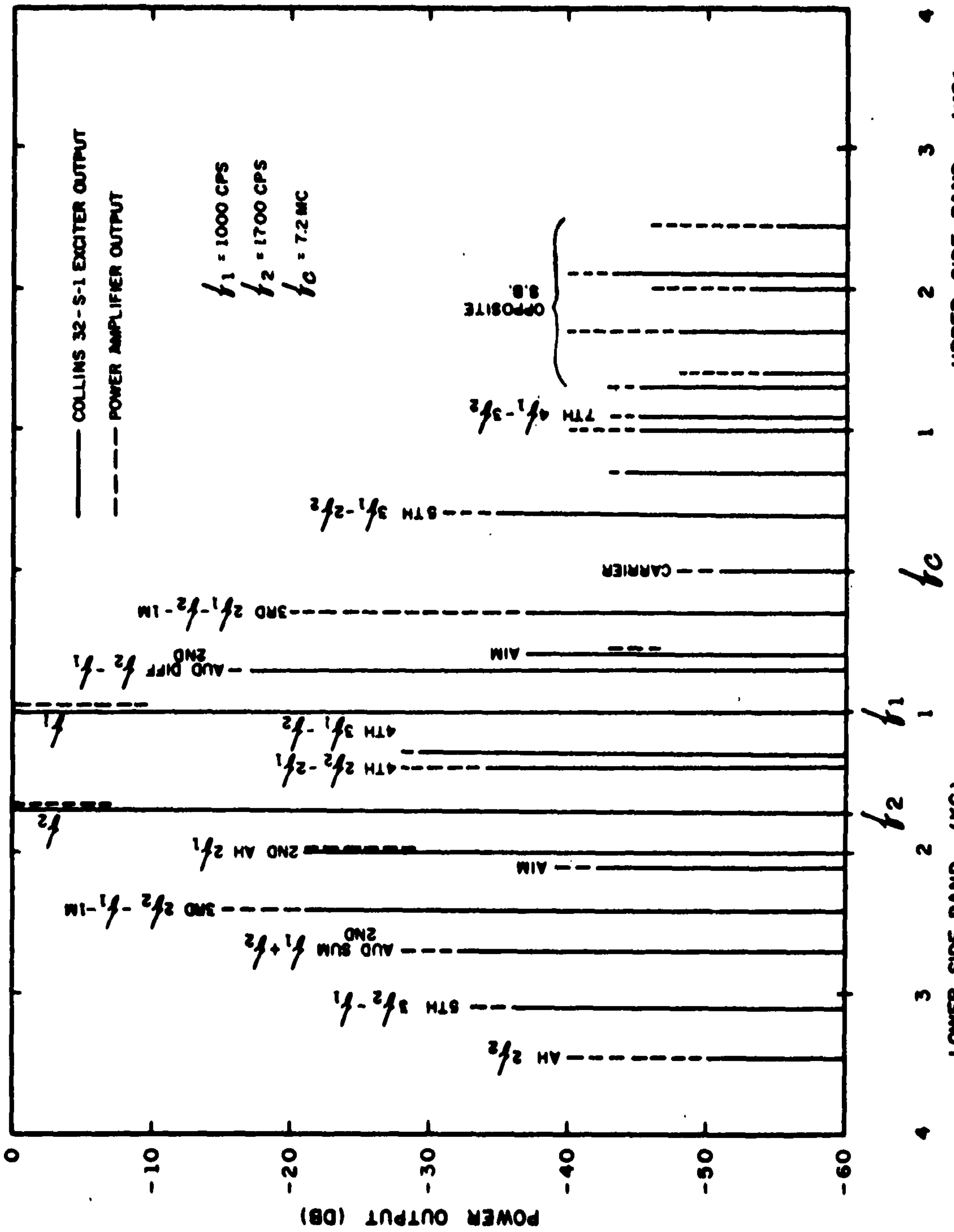

FIGURE 8 - Results of Spurious Output Two-Tone Test

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